RECOVERY OF WATER FROM BOILER FLUE GAS

QUARTERLY REPORT FOR THE PERIOD
January 1, 2006 to March 31, 2006

by

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Report Issued April 2006

DOE Award Number DE-FC26-06NT42727

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EXECUTIVE SUMMARY

Background

This project is developing new designs for condensing heat exchangers to recover water vapor from flue gas at coal-fired power plants. Pilot scale heat transfer experiments performed using boiler flue gas will determine the extent to which the condensation processes for water and acid vapors can be made to occur separately in different heat transfer sections. Both smooth wall tube and fin-tube heat transfer bundle designs for condensation of water vapor will be developed and tested. Boiler and turbine cycle analyses will be performed to determine potential heat rate gains from recovering sensible and latent heat from flue gas.

Results

The effort this quarter focused on the design of a three stage condensing heat exchanger system which, when complete, will be tested using slip streams of flue gas at oil-fired and coal-fired boilers. The design calculations, based on standard heat exchanger design procedures, used both the ε-NTU and LMTD methods. The calculations also used the equations of conservation of mass and energy for both the flue gas and the cooling water and correlations for heat transfer coefficients obtained from the heat transfer literature.

Flue gas will be extracted from the flue gas duct at the back end of the boiler, downstream of any particle collection equipment, and connected by a rectangular duct to the inlet of the tube bundle array. The design of the tube bundle array consists of tube bundle heat exchanger sections in a rectangular duct, with the flue gas in cross flow outside of the tubes and cooling water on the inside of the tubes.

The three heat transfer sections include a high temperature section to reduce the flue gas temperature from inlet values in excess of 300°F to an exit temperature of 200°F. The intermediate heat exchanger stage, with inlet and exit flue gas temperatures of approximately 200 and 110°F will be used to remove additional sensible heat from the flue gas and serve as a buffer stage between the high temperature and low temperature sections. Duct dimensions, tube diameter and length, tube spacing and numbers of tube passes have been determined for all the heat transfer sections. All three heat transfer sections will be fabricated from smooth wall tubes, using a corrosion resistant steel alloy.

It is anticipated that most, if not all, of the sulfuric acid will condense in the high temperature section and all of the water vapor condensation will take place within the low temperature heat exchanger section. Other acids found in flue gas (for example, hydrochloric and nitric) are expected to condense either in the intermediate or low temperature section.

Once fabricated, the heat exchanger sections will be instrumented to measure water and flue gas flow rates and temperatures and tube wall temperatures at selected locations. Provisions have been made in the test section design to sample flue gas at the inlet and exits of the various sections to allow measurement of concentrations of species such as H_2O, H_2SO_4, HNO_3 and HCl. In addition, provisions have been made for collection of water condensate in the last stage for chemical analysis.

PROJECT DESCRIPTION

Background

As the U.S. population grows and demand for electricity and water increase, power plants located in some parts of the country will find it increasingly difficult to obtain the large quantities of water needed to maintain operations. Most of the water used in a thermoelectric power plant is used for cooling, and DOE has begun to focus on possible techniques to reduce the amount of fresh water needed for cooling. DOE is also placing emphasis on recovery of usable water from sources not generally considered, such as mine water, water produced from oil and gas extraction, and water contained in boiler flue gas. This project is developing designs for condensing heat exchangers for power plant applications and is evaluating the heat rate and emissions co-benefits of installing these at coal-fired power plants to recover water from flue gas.

The moisture in boiler flue gas comes from three sources … fuel moisture, water vapor formed from the oxidation of fuel hydrogen, and water vapor carried into the boiler with the combustion air. The amounts of H_2O vapor in flue gas depend heavily on coal rank. Calculation of typical coal flow rates and flue gas moisture flow rates for 600 MW pulverized coal power plants show that flue gas moisture flow rates range from nearly 200,000 to more than 600,000 lbs/hr of water. In contrast, typical cooling tower water evaporation rates for a 600 MW unit are 1.6 million lbs/hr. Thus, Powder River Basin (PRB) and lignite power plants, equipped with a means of extracting all the flue gas moisture and using it for cooling tower makeup, would be able to supply from 25% (for PRB) to 37% (for lignite) of the makeup water by this approach.

Flue gas from coal-fired boilers contains concentrations of sulfuric acid (H_2SO_4) ranging up to 50 ppm with acid dewpoints in the 230 to 300°F range. Stack emissions of H_2SO_4 from coal-fired boilers has recently emerged as a serious problem, particularly for some boilers equipped with SCR reactors for NO_x control. A side benefit of cooling the gas to remove H_2O is simultaneous removal of the vapor phase SO_3/H_2SO_4. Other acidic compounds such as nitric acid (HNO_3) and hydrochloric acid (HCl) will also be removed.

There can also be boiler efficiency and heat rate benefits from cooling the flue gas to dry it. If the rejected sensible and latent heat can be put to good use in the boiler or turbine cycle, this will result in an increase in boiler efficiency and a decrease in net unit heat rate. For example, the efficiency of a well designed boiler firing a bituminous coal would increase from 89 to approximately 96% if the gas temperature were reduced to a level sufficient to condense about one half of the flue gas moisture. In addition, the reduced stack gas flow rate would result in a smaller power requirement for the induced draft fans. Some of these gains would be balanced out by the increase in gas side pressure drop due to the moisture removal equipment.

Objectives

This project is developing new designs for condensing heat exchangers to recover water vapor from flue gas at coal-fired power plants. Pilot scale heat transfer experiments performed using boiler flue gas will determine the extent to which the condensation processes for water and acid vapors can be made to occur separately in different heat transfer sections. Both smooth wall tube and compact fin-tube heat transfer bundle designs for condensation of water vapor will be developed and tested. Boiler and turbine cycle analyses will be performed to determine potential heat rate gains from recovering sensible and latent heat from flue gas.

The project is a combination of laboratory and pilot scale experiments and computer simulations. Computer analyses will be carried out to design a fin-tube heat exchanger to condense water vapor from flue gas in an efficient manner. Laboratory and pilot plant experiments will be conducted to determine the extent to which removal of acid from flue gas and condensation of H_2O vapor can be achieved in separate stages of the heat exchanger system and additional experiments will be carried out to measure the heat transfer effectiveness of the fin-tube bundle designed for condensation of water vapor. Analyses of the boiler and turbine cycle will be carried out to estimate potential reductions in heat rate due to recovering sensible and latent heat from the flue gas.

RESULTS OF WORK DURING REPORTING PERIOD

Approach

The effort this quarter focused on the design of a three stage condensing heat exchanger system which, when complete, will be tested using slip streams of flue gas at oil-fired and coal-fired boilers. The design calculations, based on standard heat exchanger design procedures, used both the Effectiveness-NTU (ε-NTU) and the Log Mean temperature Difference (LMTD) methods. The calculations also used the equations of conservation of mass and energy for both the flue gas and the cooling water and correlations for heat transfer coefficients obtained from the heat transfer literature (References 1 to 3).

Results and Discussion

Flue gas will be extracted from flue gas duct at the back end of the boiler and connected by a rectangular duct to the inlet of the tube bundle array. The design of the tube bundle array consists of three separate tube bundle heat exchanger sections in a rectangular duct (Figure 1), with the flue gas in cross flow around the tubes and the cooling water inside of the tubes.

The three heat transfer sections include a high temperature section to reduce the flue gas temperature from inlet values in excess of 300°F to an exit temperature of 200°F. The intermediate heat exchanger stage, with inlet and exit flue gas temperatures of approximately 200 and 110°F will be used to remove additional sensible heat from the flue gas and serve as a buffer stage between the high temperature and low temperature sections. The flue gas temperature will be reduced to 90°F in the low temperature section. The three heat transfer sections will be fabricated from smooth wall tubes, using a corrosion resistant steel alloy.

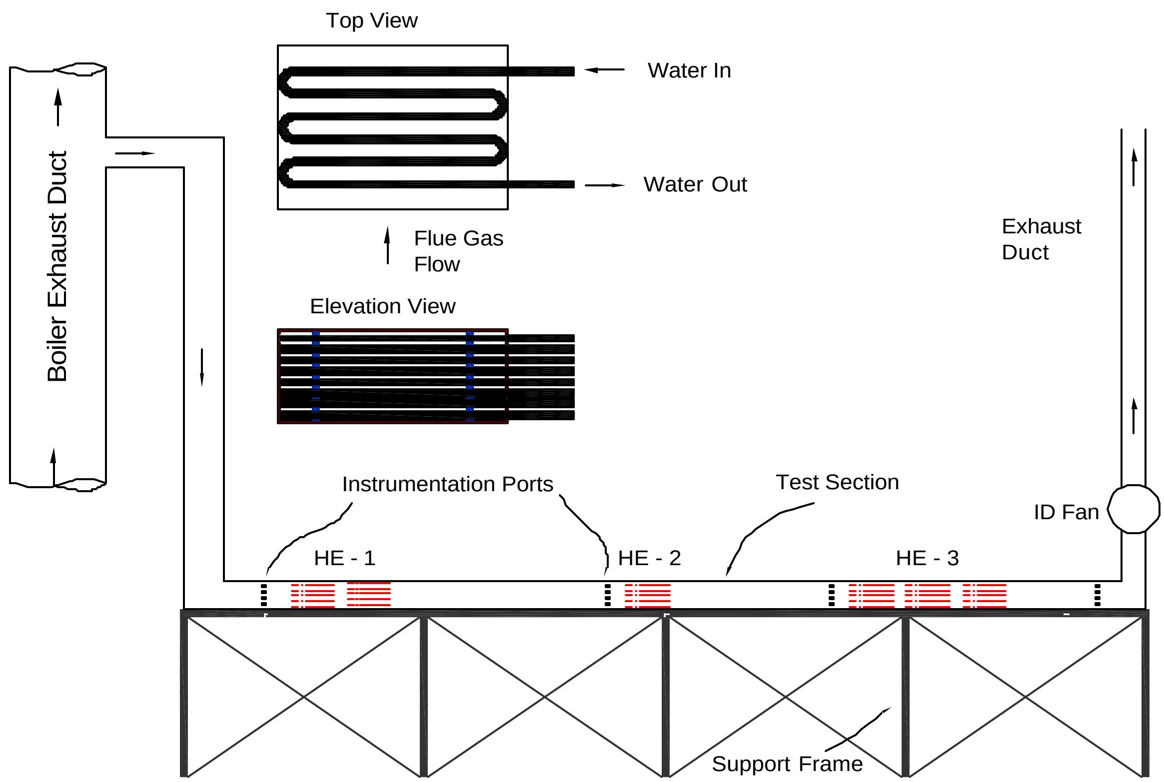

Figure 1: Diagram of Test Apparatus.

As already noted, the first low-temperature heat exchanger to be tested will be fabricated from smooth wall circular tubes. In the next phase of the project, a fin-tube bundle will be designed for use as the low temperature heat exchanger.

It is anticipated that most, if not all, of the sulfuric acid will condense in the high temperature section and that all of the water vapor condensation will take place within the low temperature heat exchanger section. Other acids found in flue gas (for example, hydrochloric and nitric) are expected to condense either in the intermediate or low temperature section.

Table 1 indicates key design parameters with values obtained from the design analysis. Duct dimensions, tube diameter and length, tube spacing and numbers of tube passes are shown for all the heat transfer sections. The tubes in all three sections will be arranged horizontally in an in-line array. The inlet duct will have a flue gas flow rate of 300 lbm/hr.

Table 1

Values of Key Design Parameters

Inputs		*Units*	HX 1	HX 2	HX 3	total
T.h.i	temperature of hot fluid in	deg F	450	222	136	
T.h.o	temperature of hot fluid out	deg F	222	136	89	
m.d.h	mass flow rate of hot fluid	lb/hr	300	300	300	
T.c.i	temperature of cold fluid in	deg F	70	70	70	
m.d.c	mass flow rate of cold fluid	lb/hr	1920	960	1730	4610
S.t	transverse tube spacing pitch	in	0.722	0.722	0.722	
S.L	longitudinal tube spacing pitch	in	1.032	1.032	1.032	
W.d	width of flue gas duct	in	14	14	14	
H.d	height of flue gas duct	in	6	6	6	
N.row	number of rows in the longitudinal direction		8	6	45	
N.t	number of rows in the transverse direction		8	8	8	
L	length of heat exchanger section	in	9.26	6.69	45	
D.o	outside diameter	in	1/2	1/2	1/2	
D.i	inside diameter	in	0.434	0.434	0.434	
Stag/Align	staggered or aligned tube configuration		align	align	align	
Outputs						
f	LMTD correction factor		1	1	0.97	
T.c.o	temperature of cold fluid out	deg F	78	76	78	
A.o	outside area of all tubes	ft^2	9.8	7.37	49.2	66.37
L.tot	total length of tubing	ft	75	56.3	422	553.3
%Ab	% duct area blocked by tubes		67	67	67	
vel.fg	velocity of flue gas	ft/s	2.9	2.4	2.12	
max vel.fg	maximum velocity of flue gas	ft/s	9.3	8	6.9	
Re.h	reynolds # for hot fluid		1330	1460	1520	
dP	gas side pressure drop	in H_2O	0.022	0.028	0.159	0.235
Nu.h	nusselt # for hot fluid		19.9	22.1	24.3	
h.h	convection coefficient for hot fluid	Btu/(hr-ft^2-deg F)	9.0	9.0	9.1	
vel.c	velocity of cooling water	ft/s	0.5	0.5	0.9	
Re.c	reynolds # for cold fluid		1840	1820	3390	
dPcw	tube side pressure drop	in H_2O	0.7	1.1	23.1	26.4
Nu.c	nusselt # for cold fluid		17.8	17.8	25.4	
h.c	convection coefficient for cold fluid	Btu/(hr-ft^2-deg F)	168	168	244	
R.w	thermal resistance of tube wall	deg F-hr/Btu	6.5E-04	4.3E-04	6.9E-05	
U	overall heat transfer coefficient	Btu/(hr-ft^2-deg F)	8.3	8.3	8.5	
UA	UA supplied by arrangement	Btu/(hr-deg F)	40.7	61.0	417	560.8
weight		lb	5.4	8.2	62.6	81.6

Once fabricated, the heat exchanger sections will be instrumented to measure water and flue gas flow rates and temperatures and tube wall temperatures at selected locations. Provisions have been made in the test section design to sample flue gas at the inlet and exits of the various sections to allow measurement of concentrations of species such as H_2O, H_2SO_4, HNO_3 and HCl. In addition, provisions have been made for collection of water condensate in the last stage for chemical analysis.

Conclusions

The design of the smooth wall tube test apparatus is nearly complete. Flue gas will be extracted from flue gas duct at the back end of the boiler and connected by a rectangular duct to the inlet of the tube bundle array. The design of the tube bundle array consists of three separate tube bundle heat exchanger sections in a rectangular duct, with the flue gas in cross flow around the tubes and the cooling water inside of the tubes.

The three heat transfer sections include a high temperature section to reduce the flue gas temperature from inlet values in excess of 300°F to an exit temperature of 200°F. The intermediate heat exchanger stage, with inlet and exit flue gas temperatures of approximately 200 and 110°F will be used to remove additional sensible heat from the flue gas and serve as a buffer stage between the high temperature and low temperature sections. The flue gas temperature will be reduced to 90°F in the low temperature section.

It is anticipated that most, if not all, of the sulfuric acid will condense in the high temperature section and that all of the water vapor condensation will take place within the low temperature heat exchanger section. Other acids found in flue gas (for example, hydrochloric and nitric) are expected to condense either in the intermediate or low temperature section.

The tubes in all three sections will be arranged horizontally in in-line arrays. Duct dimensions, tube diameter and length, tube spacing and numbers of tube passes have been determined for all the heat transfer sections.

REFERENCES

1. Incropera, F. and D. Dewitt, Fundamentals of Heat and Mass Transfer, 3rd edition, John Wiley & Sons, 1990.

2. Kakac, S. et al., Heat Exchangers, Hemisphere Publishing Corp., New York, 1981.

3. Kays, W. and A. London, Compact Heat Exchangers, 3rd edition, McGraw Hill, New York, 1984.

COST STATUS

COST PLAN/STATUS

Baseline Reporting Quarter	YR 1 Start: 1/1/06		End: 12/31/06		YR 2 Start: 1/1/07		End: 12/31/07		YR 3 Start: 1/1/08 End: 6/30/08	
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
Baseline Cost Plan (from SF-424A)	(From 242A, Sect. D)				(From 242A, Sect. D)					
Federal Share	$55,273	$55,273	$55,273	$55,273						
Non-Federal Share	$14,905	$14,905	$14,905	$14,905						
Total Planned (Federal and Non-Federal)	$70,178	$70,178	$70,178	$70,178						
Cumulative Baseline Cost	$70,178	$140,356	$210,534	$280,711						
Actual Incurred Costs										
Federal Share	$1,711									
Non-Federal Share	$12,107									
Total Incurred Costs-Quarterly (Federal and Non-Federal)	$13,818									
Cumulative Incurred Costs	$13,818									
Variance										
Federal Share	($53,562)									
Non-Federal Share	($2,798)									
Total Variance-Quarterly (Federal and non-Federal)	($56,360)									
Cumulative Variance	($56,360)									

MILESTONE PLAN AND STATUS

The Milestones identified below serve as the baseline for tracking performance of the project.

FY06 Q2: Initiate design of the smooth tube test apparatus.

FY06 Q3: Perform analyses in order to design fin-tube bundle.

FY06 Q4: Begin fabrication of the fin-tube bundle.

FY07 Q1: Perform smooth tube tests at Lehigh's oil-fired boiler.

FY07 Q2: Perform fin-tube array tests at Lehigh's oil-fired boiler.

FY07 Q3:	Analyze oil-fired boiler test data and attempt to determine effects of flue gas composition and temperature on water condensation.
FY07 Q4:	Set-up and run first round of tests at pilot scale coal-fired boiler.
FY08 Q1:	Run remaining tests with fin-tube array at pilot scale coal-fired boiler.
FY08 Q2:	Perform heat rate analyses to estimate potential reductions in heat rate due to recovering heat from flue gas.
FY08 Q3:	Begin project final report preparation.

Status

The design of the smooth wall tube test apparatus was initiated in FY06 Q2. As of March 31, 2006, the design was approximately 90 percent complete and there had been discussions with potential fabricators.

SIGNIFICANT ACCOMPLISHMENTS … None in FY06 Q2

PROBLEMS/DELAYS … None in FY06/Q2

PRODUCTS PRODUCED/TECHNOLOGY TRANSFER ACTIVITIES … None in FY06Q2